

A Search for leptophilic Z_l boson at future linear colliders

S.O. Kara,^{1,*} M. Sahin,^{2,†} S. Sultansoy,^{2,3,‡} and S. Turkoz^{1,§}

¹*Ankara University, Physics Department, Ankara, Turkey*

²*TOBB University of Economics and Technology, Physics Division, Ankara, Turkey*

³*Institute of Physics, National Academy of Sciences, Baku, Azerbaijan*

Abstract

We study the possible dynamics associated with leptonic charge in future linear colliders. Leptophilic massive vector boson, Z_l , have been investigated through the process $e^+e^- \rightarrow \mu^+\mu^-$. We have shown that ILC and CLIC will give opportunity to observe Z_l with masses up to the center of mass energy if the corresponding coupling constant g_l exceeds 10^{-3} .

*Electronic address: sokara@science.ankara.edu.tr

†Electronic address: m.sahin@etu.edu.tr

‡Electronic address: ssultansoy@etu.edu.tr

§Electronic address: turkoz@science.ankara.edu.tr

1. Introduction

Historically baryon and lepton number's conservations had been proposed to explain non observation of certain processes such as $p \rightarrow e^+ \gamma$ etc. Even though these conserved quantities are not the outcome of the standard model (SM), they can be incorporated into the SM as accidental global symmetries. It is natural to consider possible gauging of these numbers in analogy with gauging of electric charge in QED. The gauging of the baryon and lepton numbers has a long history. In 1955 Lee and Yang proposed massless baryonic “photon” [1], later in 1969 Okun considered massless leptonic “photon” [2] in analogy with the baryonic photon. However, the experiments on the equivalence of inertial and gravitational masses have put very strong limits on the strength of corresponding coupling constants, namely, $\alpha_B < 10^{-47}$ and $\alpha_L < 10^{-49}$ for baryonic and leptonic photons respectively. Comparing these with $\alpha_{EM} \approx 10^{-2}$ has led to the conclusion that massless baryonic and leptonic photons are not exist in nature. The interest on leptonic photon has been revived in 1995 [3] with the consideration of possible compensation of leptonic charge of matter by relic anti-sneutrinos foreseen by the standard big bang theory and SUSY. It was shown that the available experimental data admit the additional range for the leptonic interaction constant namely $10^{-38} < \alpha_L < 10^{-14}$ as a consequence of this compensation. This result has led to a number of studies on the subject [4–11].

It should be noted that there is no compensation mechanism for baryonic charge. For this reason massive baryonic vector boson has been proposed for baryonic charge [12, 13] and it was shown “that a new gauge boson γ_B coupling only to baryon number is phenomenologically allowed, even if $m_B < m_Z$ and $\alpha_B \approx 0.2$ ”. On the other hand gauging of B-L [14, 15] is natural in the framework of Grand Unification Theories. Manifestations of the Z' boson of the minimal B-L model at future linear colliders and LHC have been considered in recent paper [16]. Table 1 reflects today's status of B, L and B-L studies. As it seen from the Table the massive leptonic boson, as well as massless B-L boson have not been considered so far.

In this paper we have considered phenomenology of massive $U(1)$ boson coupled to lepton charge (leptophilic/quarkophobic Z_l). In section 2, the model has been formulated. Production of leptophilic Z_l at future lepton colliders (ILC/CLIC) is analyzed in section 3. In the final section the results obtained are summarized.

	massless	massive
B	+	+
L	+	-
B-L	-	+

Table I: Status of the studies related to B, L and B-L gauge bosons: plus sign indicates the subject have been considered.

2. The Model

To gauge the leptonic quantum number in our model we add a new $U'_l(1)$ gauge symmetry to standard model (SM) gauge group ($SU_C(3) \times SU_W(2) \times U_Y(1)$). It should be noted that the experimental discovery of neutrino oscillations [17] has invalidated the idea of conservation of electron, muon and tau lepton charges individually. In our model we consider single lepton charge which is the same for e , μ , τ and corresponding neutrinos. In the model, the interaction of the electroweak vector bosons with fermions and Higgs fields is introduced through the following replacement in the free fields Lagrangian:

$$\partial_\mu \rightarrow D_\mu = \partial_\mu - ig_2 \mathbf{T} \cdot \mathbf{A}_\mu - ig_1 \frac{Y}{2} B_\mu - ig_l a_l B'_\mu \quad (1)$$

where g_2 , g_1 and g_l are interaction constants, \mathbf{T} is an isospin operator of a corresponding multiplet of fermionic or Higgs fields, Y is hypercharge and a_l is lepton charge of the corresponding multiplet, \mathbf{A}_μ , B_μ , B'_μ are gauge fields. Higgs field with lepton charge must be added to provide mass to leptophilic Z_l boson which in our model coincides with B'_μ vector field. Interaction Lagrangian, obeying the $SU_C(3) \times SU_W(2) \times U_Y(1) \times U'_l(1)$ gauge symmetry, can be decomposed as:

$$L = L_{SM} + L' \quad (2)$$

where L_{SM} is standard model Lagrangian and L' is given by:

$$L' = \frac{1}{4} F'_{\mu\nu} F^{\mu\nu} + g_l J_{lep}^\mu B'_\mu + (D_\mu \Phi)^\dagger (D^\mu \Phi) + \mu^2 |\Phi|^2 - \lambda |\Phi|^4 \quad (3)$$

where

$$F'_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu \quad (4)$$

is field strength tensor,

$$J_{lep}^\mu = \sum_l a_l [\bar{\nu}_l \gamma^\mu \nu_l + \bar{l} \gamma^\mu l] \quad (5)$$

is leptonic current interacting with leptophilic Z_l , Φ is singlet complex scalar Higgs field. To avoid the triangular anomalies the following condition should be satisfied in our model

$$\sum_l a_l = 0. \quad (6)$$

As mentioned before, the experimental data on neutrino oscillations requires the same leptonic charge for e , μ , τ and corresponding neutrinos ($a_e = a_\mu = a_\tau = 1$). Therefore, additional fermion families are needed to satisfy the condition (6). It is known that recent precision electroweak data allows the existence of the fourth SM family [18–33]. In this case to satisfy the above condition in our model we take lepton charge of the fourth family leptons is equal to -3 [13, 34].

3. Production of the leptophilic Z_l boson at future linear colliders

For numerical calculations we implement the Lagrangian (3) into the CALCHEP Simulation Program [35]. In new generation linear colliders initial state radiation (ISR) and beamstrahlung (BS) will be important. Therefore, we use beam design parameters given in table 2 [36–38].

Before proceeding to calculations we ought to define the parameter space of our model compliant with existing experimental constraints. Limits from precision electroweak data on different kinds of Z' bosons have been obtained in [39, 40]. We decided to use here the conservative constraint from [39]:

$$\frac{M_{Z_l}}{g_l} \geq 7 TeV. \quad (7)$$

For given mass values the upper bounds of coupling constants obeying constraint (7), are displayed in table 3.

Collider Parameters	ILC	CLIC	
$E(\sqrt{S})$ TeV	0.5	0.5	3
$L(10^{34} \text{ cm}^{-2}\text{s}^{-1})$	2	2.3	5.9
$N(10^{10})$	2	0.68	0.372
$\sigma_x(\text{nm})$	640	202	45
$\sigma_y(\text{nm})$	5.7	2.3	1
$\sigma_z(\mu\text{m})$	300	44	44

Table II: Main parameters of ILC and CLIC. Here N is the number of particles in bunch, σ_x and σ_y are RMS transverse beam sizes at Interaction Points (IP), σ_z is the RMS bunch length.

$M_{Z_l}(\text{TeV})$	g_l
0.5	0.07
1.0	0.14
1.5	0.21
2.0	0.28
2.5	0.35
3.0	0.42

Table III: Upper bounds of the coupling constant for different values of Z_l mass.

In all calculations we have done, our signal process is $e^+e^- \rightarrow \gamma, Z, Z_l \rightarrow \mu^+\mu^-$ and background process is $e^+e^- \rightarrow \gamma, Z \rightarrow \mu^+\mu^-$. This process is chosen because it is more clean than other possible processes: Final state containing e^+e^- pair has a huge background (i.e. due to bhabha scattering); $\tau^+\tau^-$ pair will complicate the signal due to τ decays ; $\bar{\nu}\nu$ pair final states are unobservable.

In Figure 1(2) cross section versus M_{Z_l} at ILC (CLIC with $\sqrt{S} = 0,5$ TeV) is plotted for different values of coupling constant. It is seen that the signal is well above the SM background even for small values of g_l . For the mass values less than 0.5 TeV the signal is above the background due to positive interferences between γ, Z and Z_l . Comparing Figure 1 and 2 show that ILC is advantageous for $M_{Z_l} \approx 0.5$ TeV, whereas for smaller values of M_{Z_l} CLIC gives larger difference between signal and background.

Cross section versus M_{Z_l} for CLIC with $\sqrt{S} = 3$ TeV is plotted in Figure 3, where the

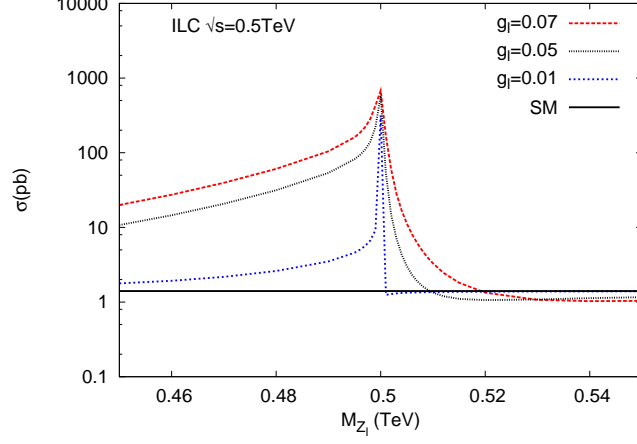


Figure 1: Cross section versus Z_l mass for different coupling values and SM background at ILC with $\sqrt{S} = 0.5$ TeV

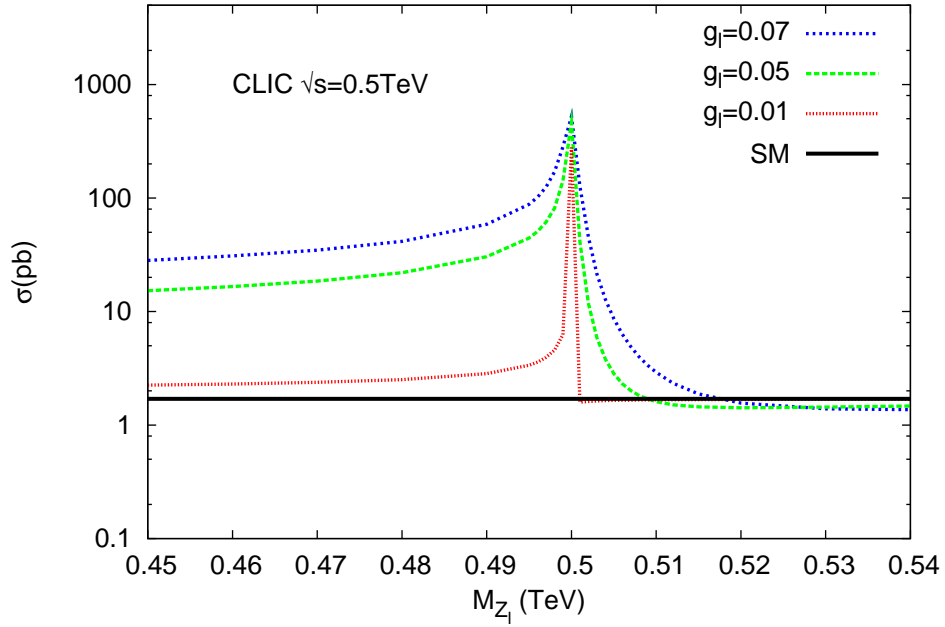


Figure 2: Cross section versus Z_l mass for different coupling values and SM background at CLIC with $\sqrt{S} = 0.5$ TeV.

shift of the cross section peak from center of mass energy is clearly seen, especially for large values of g_l . This shift is a consequence of ISR and BS.

In order to show the effects of ISR and BS together with machine design parameters we present the Figure 4 where cross section versus mass is plotted for three different cases:

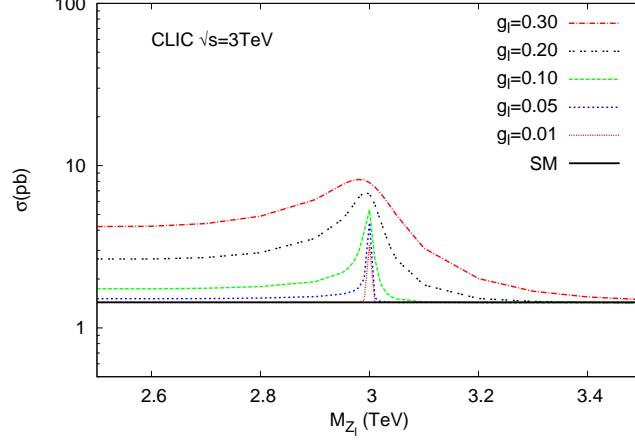


Figure 3: Cross section versus Z_l mass for different coupling values and SM background at CLIC with $\sqrt{S} = 3$ TeV.

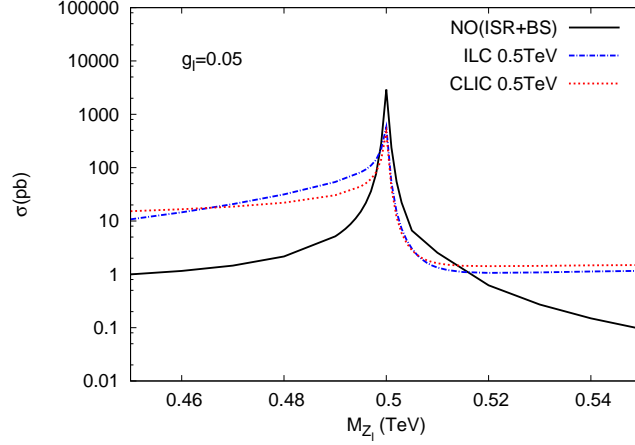


Figure 4: ISR and BS effects at ILC and CLIC with $\sqrt{S} = 0.5$ TeV.

$\sqrt{S} = 0.5$ TeV without ISR and BS, ILC with ISR and BS and $\sqrt{S} = 0.5$ TeV CLIC with ISR and BS. It is seen that ISR and BS essentially reduce cross section at $M_{Z_l} \approx \sqrt{S}$, whereas cross section in tails is increased by an order.

Figure 5 presents effects of ISR and BS depending on coupling constant g_l for ILC and CLIC with $\sqrt{S} = 0.5$ TeV. One can see that these effects essentially reduce corresponding cross section especially at lower values of g_l . Furthermore, cross section at ILC exceeds that of CLIC ($\approx 25\%$).

The ISR and BS effects at CLIC with $\sqrt{S} = 3$ TeV are presented in Figure 6. As expected, ISR and BS effects are more efficient at higher energies: for $g_l = 0.05$ reduction factor are 6

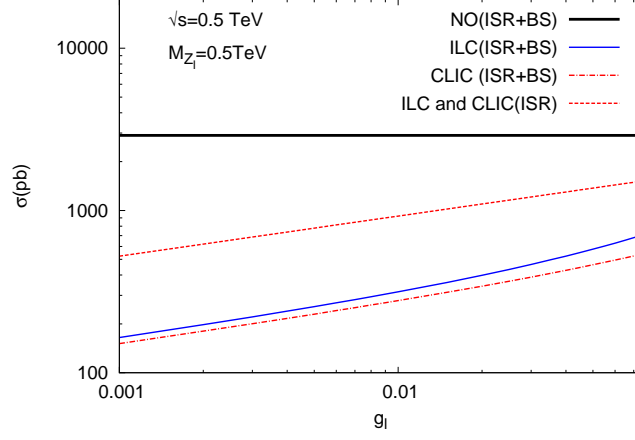


Figure 5: ISR and BS effects depending on g_l at ILC and CLIC with $\sqrt{S} = 0.5$ TeV

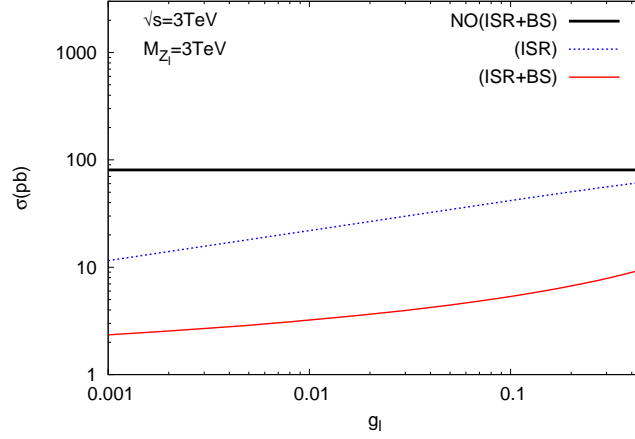


Figure 6: ISR and BS effects depending on g_l at CLIC with $\sqrt{S} = 3$ TeV.

and 18 at $\sqrt{S} = 0.5$ TeV and 3 TeV, respectively.

In order to determine discovery potential of ILC and CLIC, we have used following cuts: $|M_{inv}(\mu^+\mu^-) - M_{Z_l}| < 10 \text{ GeV}$ and $|\eta_\mu| < 2$. Statistical significance (S) is calculated using the following formula:

$$S = \frac{\sigma_{signal} - \sigma_{SM}}{\sqrt{\sigma_{SM}}} \sqrt{L_{int}} \quad (8)$$

In Figure 7(8) we plot 3σ and 5σ contours against M_{Z_l} and g_l for ILC (CLIC with $\sqrt{S} = 0.5$ TeV). It is seen that both ILC and CLIC will give opportunity to search leptophilic Z_l in the range from 300 to 500 GeV down to $g_l \approx 10^{-3}$. However, for high mass values the CLIC

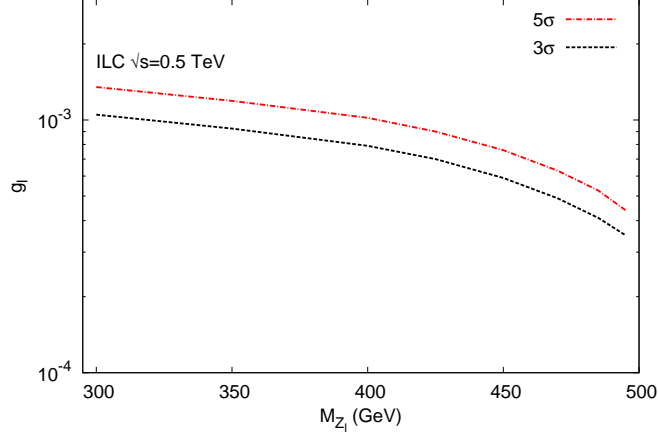


Figure 7: Achievable limits for the mass and coupling parameters for 3σ observations and 5σ discovery at ILC with $\sqrt{S} = 0.5$ TeV.

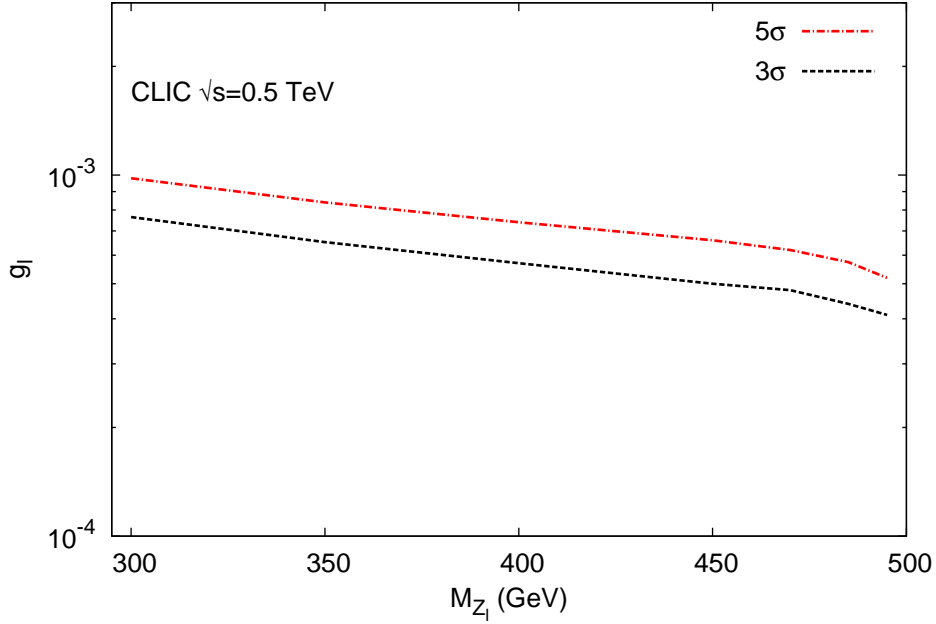


Figure 8: Achievable limits for the mass and coupling parameters for 3σ observations and 5σ discovery at CLIC with $\sqrt{S} = 0.5$ TeV.

and for low mass values the ILC is advantageous. Similar plots for CLIC with $\sqrt{S} = 3$ TeV are given in Figure 9 showing that Z_l could be covered up to $M_{Z_l} = 3$ TeV of $g_l \geq 10^{-3}$.

In Figure 10 we plotted the invariant mass distribution of final muons for signal and SM background. It is clear that the signal is well above the background.

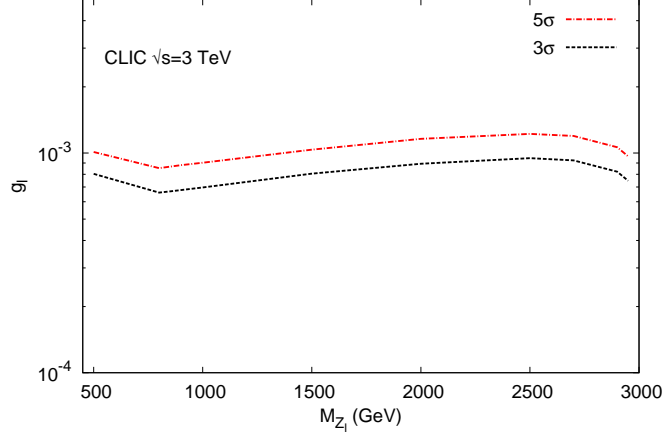


Figure 9: Achievable limits for the mass and coupling parameters for 3σ observations and 5σ discovery at CLIC with $\sqrt{S} = 3$ TeV.

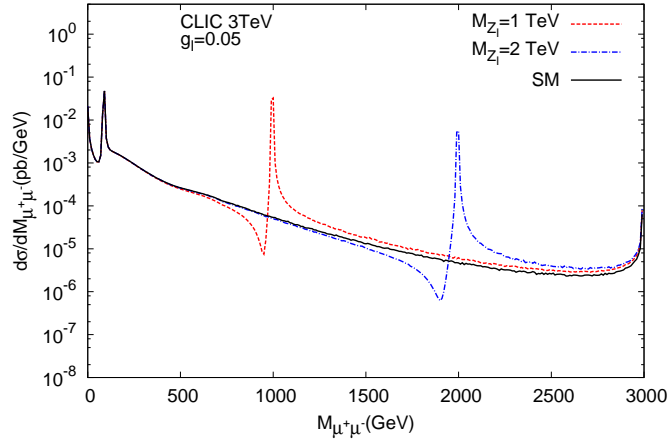


Figure 10: Invariant mass distributions of final muons for SM background and signal. Two different values of M_{Z_l} have been used.

4. CONCLUSION

By investigating the process $e^+e^- \rightarrow \mu^+\mu^-$, we have shown that future linear colliders will give opportunity to observe leptophilic vector boson with masses up to the center of mass energy if $g_l \geq 10^{-3}$. As a result of the calculations done, we could say that initial state radiation and beamstrahlung will have important impact for leptophilic Z_l vector boson at future linear colliders. In our calculations we have ignored possible impact of fourth family leptons on the process when $M_{Z_l} > 2M_{l_4}(M_{\nu_4})$. The work on the subject is ongoing and

results will be published elsewhere.

Finally, massless boson connected to B-L will be considered in separate paper [41].

Acknowledgments

This work is supported by DPT and TUBITAK.

-
- [1] T.D. Lee, C. N. Yang, Phys. Rev. 98 (1955) 1501.
 - [2] L.B. Okun, Yad Fiz. 10 (1969) 358 (in Russian); Sov. J. Nucl. Phys. 10 (1969) 206 (in English)
 - [3] A.K. Ciftci, S. Sultansoy, S. Turkoz, Phys. Lett. B 355 (1995) 494.
 - [4] L.B. Okun, Phys. Lett. B 382 (1996) 389.
 - [5] L.B. Okun, Modern Phys. Lett. A 11 (1996) 3041.
 - [6] B.V. Martemyanov, JETP Lett. 66 (1997) 547.
 - [7] S.N. Gninenko, Phys. Lett. B 413 (1997) 365.
 - [8] V.A. Ilyin, L.B. Okun, A.N. Rozanov, Nucl. Phys. B 525 (1998) 51.
 - [9] B. Akkus, E. Arik, R. Beyer, et al. , Phys. Lett. B 434 (1998) 200.
 - [10] A.D. Dolgov, Phys. Reports 320 (1999) 1.
 - [11] J.W. Brockway, Phys.Lett. B 682 (2010) 342.
 - [12] C.D. Carone, H. Murayama, Phys Rev. Lett. 74 (1995) 3122.
 - [13] C.D. Carone, H. Murayama, Phys Rev. D 52 (1995) 484.
 - [14] W. Buchmüller, C. Greub, P. Minkowski, Phys. Lett. B 267 (1991) 395.
 - [15] K. Shaaban, Phys. Rev. D 82 (2010) 077702.
 - [16] L. Basso, A. Balyaev, S. Moretti, G.M. Pruna, JHEP 10 (2009) 006.
 - [17] K. Nakamura *et al.* , (Particle Data Group) , J. Phys. G 37 (2010) 075021.
 - [18] M. Maltoni *et al.*, Phys. Lett B 476 (2000) 107.
 - [19] H.-J. He, N. Polonsky and S. Su, Phys. Rev. D 64 (2001) 053004.
 - [20] M.I. Vysotsky, Acta Phys. Slov. 52 (2002) 199.
 - [21] V.A. Novikov *et al.*, JETP Lett. 76 (2002) 127.
 - [22] S.S. Bulanov *et al.*, Phys. Atom. Nucl. 66 (2003) 2169.
 - [23] V.A. Novikov *et al.*, Phys. Atom. Nucl. 73 (2010) 636.

- [24] J. Alwall *et al.*, Eur. Phys. J. C 49 (2007) 791.
- [25] G. Kribs *et al.*, Phys. Rev. D 76 (2007) 075016.
- [26] M. Bobrowski *et al.*, Phys. Rev. D 79 (2009) 113006.
- [27] M. S. Chanowitz, Phys. Rev. D 79 (2009) 113008.
- [28] M. Hashimoto, Phys. Rev. D 81 (2010) 075023.
- [29] O. Ebberhardt, A. Lenz and J. Rohrwild, Phys. Rev. D 82 (2010) 095006.
- [30] O. Cobanoglu *et al.*, arXiv:1005.2784 [hep-ph].
- [31] <http://projects.hepforge.org/opucem/>
- [32] J. Erler and P. Langacker, Phys. Rev. Lett. 105 (2010) 031801.
- [33] M. Sahin, S. Sultansoy, S. Turkoz, Phys. Rev. D 83 (2011) 054022.
- [34] P.F. Perez, M. B. Wise, Phys. Rev. D 82 (2010) 011901.
- [35] A. Pukhov, *et al.*, hep-ph/9908288.
- [36] J. Brau *et al.*, ILC reference design report vol. 3: Accelerator, ILC REPORT–2007–001(2007).
- [37] H. Braun *et al.*, CLIC 2008 parameters, CERN report No. CERN-OPEN-2008-21, CLIC-NOTE- 764, Geneva (2008).
- [38] <http://clic-meeting.web.cern.ch/clic-meeting/clictable2010.html>, CLICPARAMETER LIST 3 TeV.
- [39] G. Cacciapaglia, C. Csaki, G. Marandella and A. Strumia, Phys. Rev. D 74 (2006) 033011.
- [40] F. del Aguila, J. de Blas and M. Perez-Victoria, JHEP 1009 (2010) 033.
- [41] S. O. Kara, S. Turkoz, in preparation.